In Situ Chemical Oxidation

Introduction:

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Regulatory Acceptance for New Solutions

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Purpose of ITRC

ITRC is a state-led, national coalition of regulators and others working to

- improve state permitting processes and
- speed implementation of new environmental technologies.

Goals

- Achieve better environmental protection through innovative technologies
- Reduce the technical/regulatory barriers to the use of new environmental technologies
- Build confidence about using new technologies

Other Participants

- Industry representatives
- Academia
- Public stakeholders
- Federal agencies
  - U.S. Department of Energy
  - U.S. Environmental Protection Agency
  - U.S. Department of Defense
- Host organization
  - ECOS Environmental Council of the States
- State organizations
  - Western Governors' Association
  - Southern States Energy Board

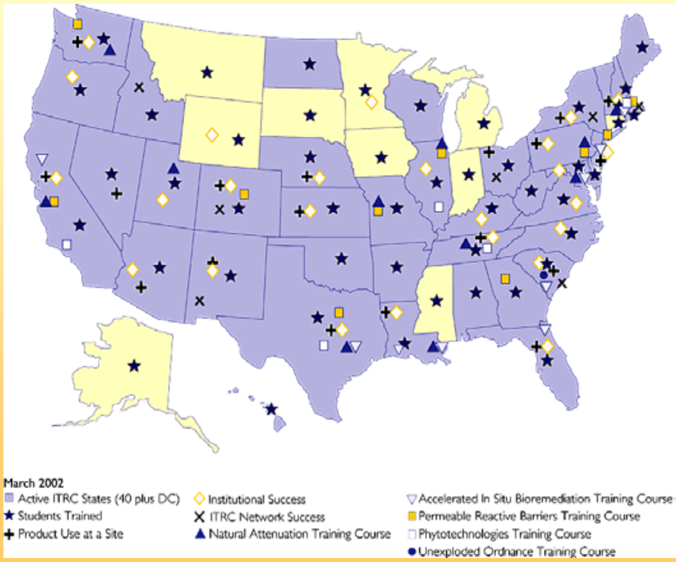
Products & Services

- Regulatory and Technical Guidelines
- Technology Overviews
- Case Studies
- Peer Exchange
- Technology Advocates
- Classroom Training Courses
- Internet-Based Training Sessions

Active Technical Teams

- Alternative Landfill Technologies
- Brownfields
- Constructed Wetlands
- Contaminated Sediments
- Dense Nonaqueous Phase Liquids
- Diffusion Samplers
- DOE Gate 6 Technologies
- In Situ Bioremediation
- MTBE-Contaminated Groundwater
- Permeable Reactive Barriers
- Radionuclides
- Remedial Process Optimization
- Sampling, Characterization, and Monitoring
- Small Arms Firing Range
- Unexploded Ordnance

Nationwide Success



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Technical Program

NJDEP, Moderator

Available Oxidants and Oxidant Selection
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XPERT DESIGN & DIAGNOSTICS, LLC

Laboratory and Field Pilot Test Design
Dr. John Cookson
XPERT DESIGN & DIAGNOSTICS, LLC

Full-Scale Design and Implementation
Kenneth L. Sperry, P.E. and Dr. John Cookson
XPERT DESIGN & DIAGNOSTICS, LLC

In Situ Chemical Oxidation: Design & Implementation

October 30, 2002

NJDEP Public Hearing Room

Sponsors: NJDEP & ITRC

Presented by

Kenneth L. Sperry, P.E.

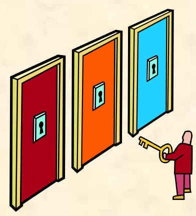
John Cookson, Jr., Ph.D.

XPERT DESIGN and DIAGNOSTICS, LLC

22 Marin Way, Stratham, NH

www.XDD-LLC.com

Available Oxidants



Available Oxidants

Oxidant	Potential (V)	Form	Cost/ equiv
Fenton's Reagent (OH•)	2.8	Liquid	___
Perozone (O_3 + Peroxide)	2.8	Gas/Liquid	___
Activated Persulfate (SO_4^{-}•)	2.6	Salt Liquid	___
Ozone (O_3)	2.42 2.07	Gas	0.020 0.053
Persulfate ($S_2O_8^{2-}$)	2.01	Salt Liquid	0.030
Hydrogen Peroxide (H_2O_2)	1.78	Liquid	0.026
Permanganate (MnO_4^{-})	1.68	Salt Liquid	0.017 - K 0.031 - Na

Costs adapted from Siegrist et al., 2001

Permanganate – MnO_4^-

- **$KMnO_4$ Salt**
- **$NaMnO_4$ Solution (40%)**

Source: XDD, LLC

Direct Oxidation

$$MnO_4^- + 4H^+ + 3e^- \rightarrow MnO_{2(s)} + 2H_2O$$

Permanganate – MnO_4^-

- **Used in waste water treatment for decades**
- **Used in organic chemical manufacturing**
- **Application for in-situ remediation was first recognized by Farquhar at U of Waterloo, 1989**
- **Mined from ore and therefore has other constituents or impurities**
- **Supplied in grades based on purity and flow properties**

Source: XDD, LLC

Permanganate – MnO_4^-

Advantages

- High stability in subsurface
  - Provides better overall efficiency
  - Allows for diffusion into tight soils & porous rock
- No gas/heat production - less health & safety issues
- Applicable over wide pH range
- Many successful in-situ field applications

Disadvantages

- Lower oxidation potential ∴ Narrower range of contaminant applicability
- Metal impurities in product*
- Potential pore clogging due to precipitates*

Persulfate – $S_2O_8^{2-}$

- $Na_2S_2O_8$ Salt
- $Na_2S_2O_8$ Solution
- Can also form free radicals through heat or transitional metals

Direct Oxidation

$$S_2O_8^{2-} + 2e^- \rightarrow 2SO_4^{2-}$$

Free Radical Formation

$$S_2O_8^{2-} + 2Fe^{+2} \text{ (or Heat)} \rightarrow 2SO_4^{-\bullet} + 2Fe^{3+}$$

Persulfate – $S_2O_8^{2-}$

- Used in polymerization and organic chemical manufacturing
- Used in pulp and paper industry
- Used in electronics as an etchant
- Used as soil stabilizer
- Recently being used for in-situ chemical oxidation

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Persulfate – $S_2O_8^{2-}$

Advantages

- Can be catalyzed by reduced metals or heat to promotes Sulfate Free Radical (SFR) formation
- High oxidation potential ∴ applicable to wide range of organics
- Can be combined with permanganate (DUOX)

Disadvantages

- Relatively new technology and limited field pilot studies
- Catalyst required for activated persulfate system are currently under development

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Hydrogen Peroxide – H_2O_2

- H_2O_2 solution
- Can also form free radicals through activation with transitional metals

Direct Oxidation

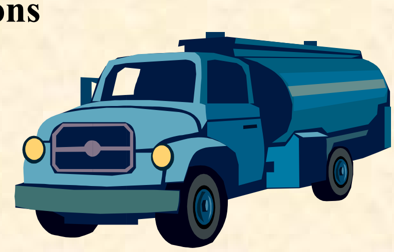
$$H_2O_2 + H^+ + e^- \rightarrow OH^- + H_2O$$

Free Radical Formation

$$H_2O_2 + Fe^{+2} + \rightarrow OH^- + OH^{\bullet} + Fe^{3+}$$

Hydrogen Peroxide – H_2O_2

- Many industrial applications
  - Effluent treatment
  - Electrical manufacturing
  - Food manufacturing
  - Pulp and Paper



- Used for in-situ remediation since 70's

Hydrogen Peroxide – H_2O_2

Advantages

- High oxidation potential ∴ applicable to wide range of organics
- The most studied of the oxidizing compounds for remediation
- Can be combined with ozone (perozone)

Disadvantages

- Reaction's gas/heat production – health & safety hazard
- Short half-life ∴ limited travel distances, requires closely spaced injection points
- Optimal pH between 3–5
- Ineffective in alkaline environments

Ozone – O_3

- Only available as a gas
- Degrades to dissolved oxygen
- Reacts with water or peroxide to produce hydroxyl-radicals

- Direct Oxidation Under Acidic pH's

$$O_3 + 2H^+ + 2e^- \rightarrow O_2 + 2H_2O$$

- Free Radical Formation

$$O_3 + OH^- \rightarrow O_2^- + HO_2^{\bullet}$$

- Criegee Oxidation (Nucleophillic Substitution)

Ozone – O_3

- Used in many processes:
  - Wastewater treatment
  - Industrial effluent treatment
  - Aquaculture
  - Bleaching
  - Drinking water
- Generated on-site due to limited stability
- Made from air or oxygen

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Ozone – O_3

Advantages

- High oxidation potential ∴ applicable to wide range of organics
- Easier to apply than liquid oxidants in vadose zone
- Generated on-site, allows for continual application
- Decomposes to oxygen which can stimulate aerobic biodegradation

Disadvantages

- Highly unstable - short half-life
- Effective distribution in saturated zone requires closely spaced injection points
- Confined aquifer usage requires pressure (gas) relief

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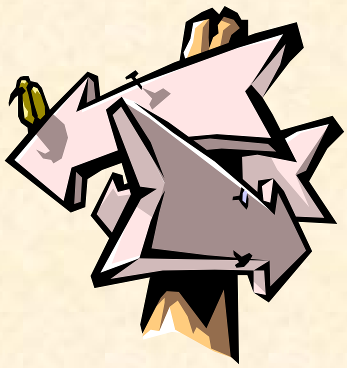
Oxidant Selection



Contaminant Type

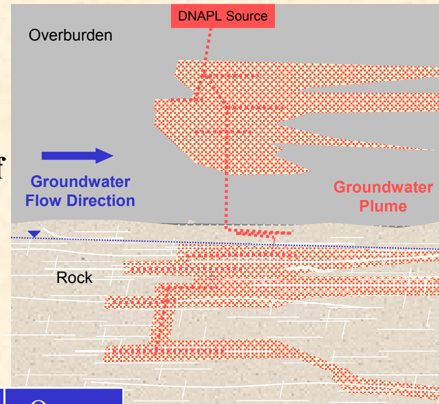
Contaminant	MnO_4	S_2O_8	$SO_4\bullet$	Fenton's	Ozone
Petroleum Hydrocarbon	G	G/E	E	E	E
Benzene	P	G	G/E	E	E
Phenols	G	P/G	G/E	E	E[1]
Polycyclic Aromatic Hydrocarbons (PAHs)	G	G	E	E	E
MTBE	G	P/G	E	G	G
Chlorinated Ethenes (PCE, TCE, DCE, VC)	E	G	E	E	E
Carbon Tetrachloride	P	P	P/G	P/G	P/G
Chlorinated Ethanes (TCA, DCA)	P	P	G/E	G/E	G
Polychlorinated Biphenyl's (PCBs)	P	P	P	P	G[1]
Energetics (RDX, HMX)	E	G	E	E	E

P = poor G = good E = excellent 1=Perozone

Contaminant Distribution

Factors Affecting Selection:

1. **Source Zone Treatment**
2. **Poorly defined or large areas of low concentrations (dissolved plumes)**



Criteria	MnO_4	S_2O_8	Fenton's	SO_4•	Ozone
1	E	E	E	E	E
2	P/G	P/G	P	P	P/G

Geologic Considerations

Unconsolidated Materials:

1. **Higher permeability sands to gravels**
   - **Advection dominated**
2. **Lower permeability silts to clays**
   - **Diffusion dominated**
3. **Combinations of lower and higher permeability zones**
   - **Advection and diffusion dominated**

Criteria	MnO_4	S_2O_8	Fenton's	SO_4•	Ozone
1	E	E	E	E	E
2	G	G	P	P	P
3	G/E	G/E	P	P	P

Geologic Considerations

__Consolidated Materials:__

1. **Secondary porosity features (fractures, parting planes, etc.)**
   - **Advection dominated**
2. **Primary porosity features**
   - **Diffusion dominated**

Criteria	MnO_4	S_2O_8	Fenton's	$SO_4•$	Ozone
1	E	E	P/G	P/G	P/G
2	G	G	P	P	P

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Hydrogeologic Considerations

__Factors that Influence Oxidant Selection Include:__

1. **Saturated zone**
2. **Unsaturated zone**
3. **Groundwater velocity**
   a) **Slow**
   b) **Fast**

Criteria	MnO_4	S_2O_8	Fenton's	$SO_4•$	Ozone
1	E	E	G	G	G
2	P/G	P/G	P/G	P/G	G
3a	G	G	P	P	P
3b	G	G	G	G	G

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Geochemical Considerations

1. **Carbonate system (free radical scavengers)**
2. **High dissolved metals (precipitation issues)**
3. **High % organic matter (f_{oc}, DOC, etc.)**

Criteria	MnO_4	S_2O_8	Fenton's	$SO_4•$	Ozone
1	E	E	P	G	P
2	P	E	E	E	P
3	P	E	P	G	P

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Additional Considerations

Criteria	MnO_4	S_2O_8	Fenton's	$SO_4•$	Ozone
Gas Production	Low	Low	High	Low	High
Heat Production	Low	Low	High	Low	Low
Fugitive Emissions	Low	Low	High	Low	High
Availability	E	E	E	E	G
Ease of Handling	G	E	G	E	G
Impact to Water Quality	Mod.	Mod.	Low	Mod.	Low
Patent Restrictions	Low	High	High	High	High
Technology Development	G	P	E	P	G
Available Information	G	P	G	P	G
Tried Field Applications	G	P	G	P	G

P = poor G = good E = excellent Mod. = Moderate

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Thank You!

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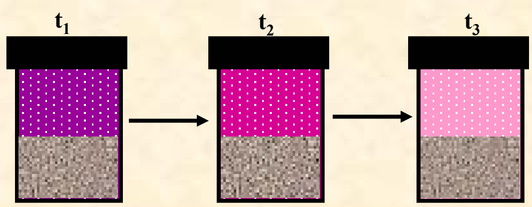
Laboratory Treatability Studies

Objectives

- Determine the ability and rate of an oxidant to destroy the target contaminants
- Determine the oxidant demand of the site soils
- Determine the by-product formation of the oxidation-reduction reactions
- Analyze potential for metals release
- Determine catalyst requirements

Soil Oxidant Demand Tests

- Often simple batch studies
- Soil added to known concentration of oxidant
- Consumption of oxidant monitored over time
- Variables
  - Time
  - Oxidant concentration
  - Catalyst concentration

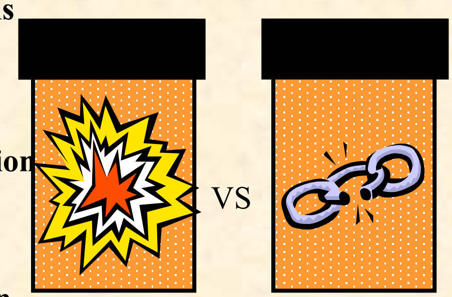


Soil Oxidant Demand Tests

- Soil demand has been shown to vary considerably between soils
- Can very <1 g/kg to >10 g/kg
- Factors affecting SOD
  - Organic matter
  - Reduced metals
  - Minerals
  - Applied oxidant concentration
- Post treatment metals can also be analyzed to determine if mobilization has occurred

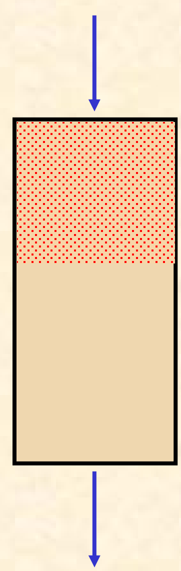
Contaminant Treatability Tests

- Often simple batch studies
- Contaminant added to known concentration of oxidant
- Contaminant Concentration Monitored overtime
- Can be run with/without soils
- Variables
  - Time
  - Contaminant concentration
  - Catalyst concentration
  - Reactant concentration
  - By-product concentration



Column Studies

- Better simulate subsurface conditions
- Variables
  - Time
  - Contaminant concentration
  - Catalyst concentration
  - Reactant concentration
  - By-Product concentration
- More Expensive



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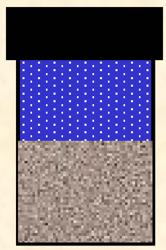
Additional Considerations

- Batch studies assume complete mixing
- May underestimate surface reactions
- Doesn’t simulate subsurface conditions and discrete chemistry (mixing fronts etc.)
- Concentration dependent



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Field Pilot Tests

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Pilot Test Objectives

- Evaluate efficacy of selected oxidant to degrade target compounds
- Evaluate oxidants affect on aquifer
  - Hydraulic conductivity
  - Geochemistry – pH, redox
  - Mobilization of naturally occurring chromium
- Determine full-scale design parameters
  - Oxidant loading
  - Injection well spacing
  - Injection pressures and flow rates

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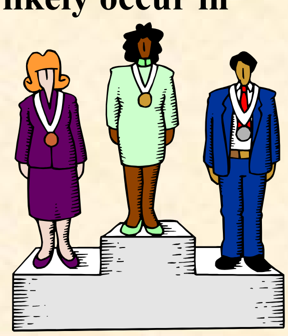
Expectations

- How do we measure success?
- Pilot test typically will not accomplish remediation clean-up goals
- Contaminant rebound will likely occur in groundwater



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Design Considerations

- Range from simple push-pull test to elaborate multi-point injection/monitoring studies
- Must account for contaminant, geology, chemistry, hydrogeology
- Regulatory considerations
  - Water quality effects
  - Off-site migration control
- Budget

OR

Pilot study design determined by goals of each study.

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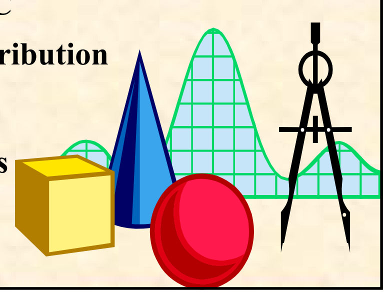
Design Considerations

- Duration
  - Must be based on site conditions
  - Reaction kinetics
  - Typically days to weeks
- Oxidant Loading
  - Need sufficient oxidant mass to affect measurable reduction in COC
  - SOD, contaminant mass, distribution
- Location
  - Representative site conditions
  - Worst case conditions



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Design Considerations
Monitoring

- **Based on rates of**
  - **Migration**
  - **Oxidant consumption**
  - **Contaminant destruction**
- **Regulatory issues**
  - **Intermediate formation**
  - **Migration**
  - **Water quality exceedences (directly or indirectly)**

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Design Considerations
Monitoring

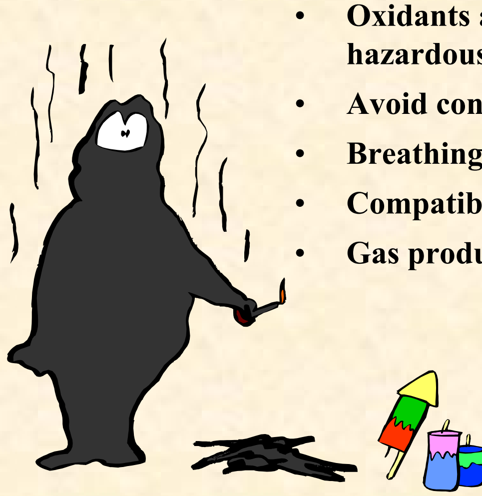
Typical Groundwater Parameters	
Parameter	**Method**
Contaminants	Varies – EPA 8260, 8270
Oxidant	Field test kit
Metals	EPA Method 200.7 (ICP), SM 3120B
Major Cations	EPA Method 200.7 (ICP), SM 3120B
Anions	EPA Method 310.1, SM 2320B
Alkalinity	EPA Method 310.1, SM 2320B
ORP (EH)	Field Measurement
pH	Field Measurement
Temp	Field Measurement
Conductivity	Field Measurement

Adapted From ITRC Technical/Regulatory Guidelines for In Situ Chemical Oxidation of Contaminated Soil and Groundwater, 2001

Design Considerations
Monitoring

- System Monitoring
  - Mass of oxidant
  - Mass of catalysts
  - Injection rates
  - Volumes
  - Pressures
  - Radius of influence

Design Considerations
Health and Safety



- Oxidants are strong chemicals – very hazardous !!
- Avoid contact with skin
- Breathing hazard with dust or mist
- Compatibility should be checked*
- Gas production / fugitive emissions

Design Considerations
Regulatory

- Safe Drinking Water Act's (SDWA) Underground Injection Control (UIC)
- Injection wells are designated as Class V under UIC and need variance or permit by rule
- Variances becoming more common and accepted
- May require permitting (RCRA) where above ground treatment, storage, or disposal occurs

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Approaches

- Site specific, depends on
  - Geology
  - Contaminant
  - Oxidant
- Must consider project goals and budget

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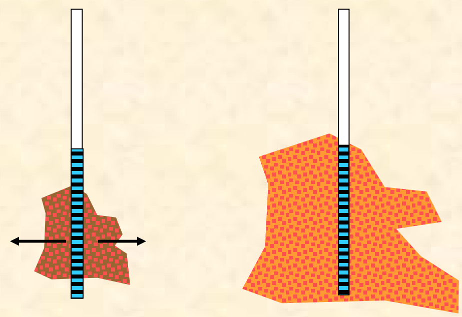
Single-Well Tests

- Push-pull tests
- Inject known volume of oxidant and conservative tracer
- Extract and analyze change
- Compare to control test



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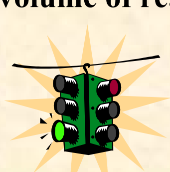
Single-Well Tests

Advantages

- Minimal equipment needs
- Short duration (1 to 3 days)
- Low cost
- Use existing well*
- Estimate of SOD
- Estimate of COC destruction
- Low volume of reagent used



Disadvantages

- Provides limited information on full-scale delivery method
- Generates groundwater that may require disposal or treatment

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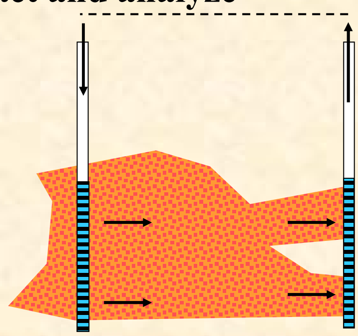
Dual Well Tests

- Injection / extraction tests (circulation tests)
- Inject known volume/mass of oxidant and conservative tracer
- Extract and analyze



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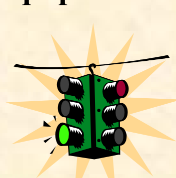
Dual Well Tests

Advantages

- Larger aquifer volume tested
- Better estimation of SOD
- Better estimation of COC destruction
- Better estimate of oxidant distribution
- Low equipment needs

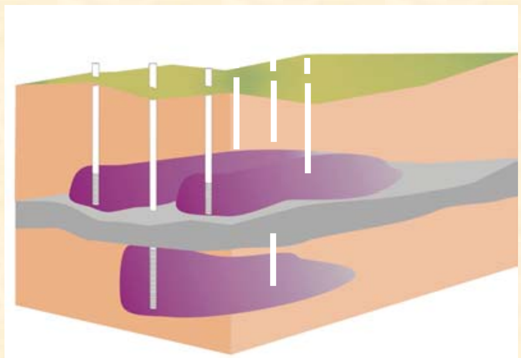


Disadvantages

- Typically requires installation of injection points/wells
- May or may not be able to re-inject extracted water
- Permitting for re-injection of extracted water
- Longer duration (1 to 2 weeks)

Multi-Well Tests

- Multi-point injection
- Inject known volume/mass of oxidant
- Monitor multiple points over time



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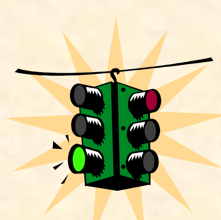
Multi-Well Tests

Advantages

- Applicable to all oxidants
- Enables better ROI determination
- Able to better simulate full-scale application

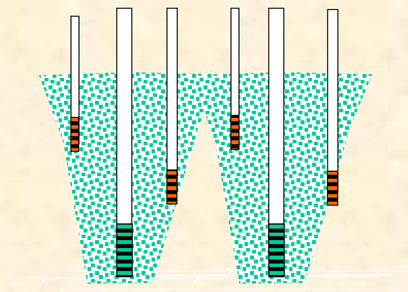
Disadvantages

- High cost ($$$)
- Requires installation of multiple wells
- Longer duration
- Higher oxidant batching/injection equip needs



Sparge Tests

- Inject known volume/mass of oxidant gas
- Monitor fugitive gas



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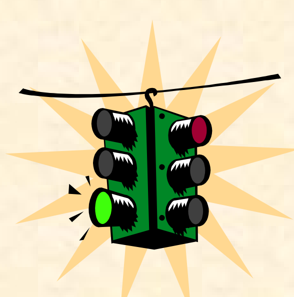
Sparge Tests

Advantages

- Good approximation of full-scale application
- Well established technique



Disadvantages

- Moderate Cost ($$)
- May require vadose monitoring or SVE
- High Equipment needs

Limitations

- Short duration
  - Mass transfer limitations
  - Limited oxidant loading
- Small treatment area
  - Variable geology
  - Variable contaminant distribution
- Limited monitoring
  - Can miss reactions – timing is important
- Cost too often dictates SOW!

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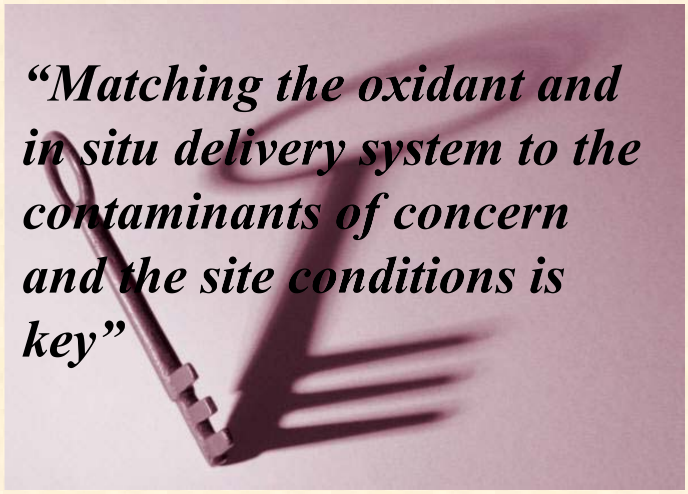
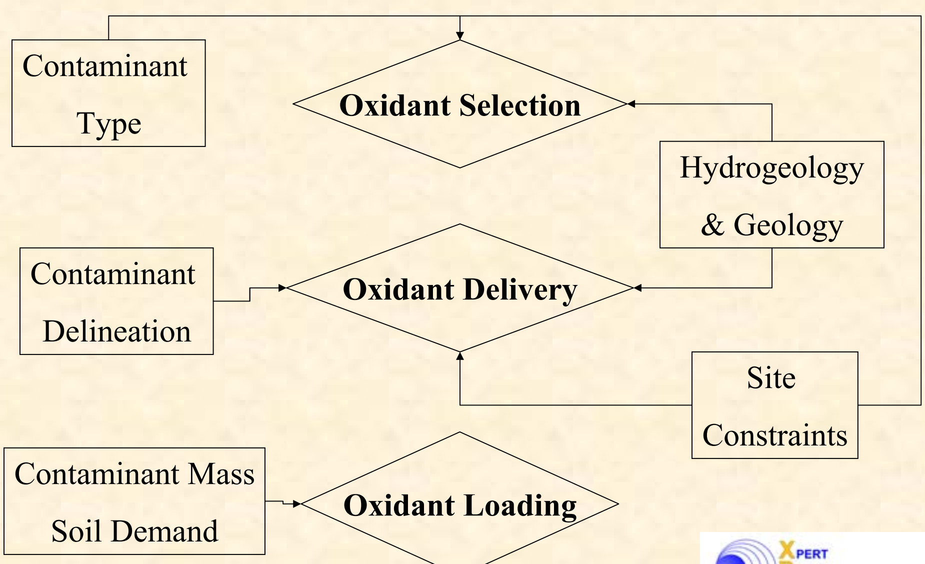
Full-Scale Application



"Matching the oxidant and in situ delivery system to the contaminants of concern and the site conditions is key"

Full-Scale Conceptual Design



Design Factors

- Primarily a source zone technology
- May be cost prohibitive for use on large diffuse plumes
- Most oxidants stimulate bioremediation
- Mass transfer limitations

ISCO & Bioremediation

- Microbial communities can temporarily be altered but usually bounce back quickly
- Often beneficial (post-oxidant injection)
  - Ozone, hydrogen peroxide provide oxygen that can stimulate aerobic biodegradation
  - Increased bioavailability of organic carbon can stimulate biodegradation (aerobic & anaerobic)
  - Increases contaminant bioavailability

Mass Transfer Limitations

- ISCO reaction kinetics vs. contaminant desorption and diffusion processes
- Contaminant rebound often observed after "batch" oxidant applications
- May necessitate multiple applications or a phased approach

Source: Pignatello and Xing (1996)

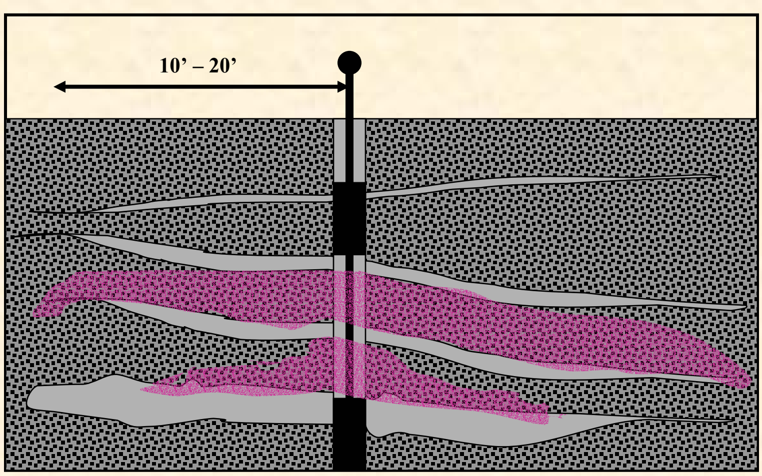
Oxidant Stability

- Stability/persistence/presence of oxidant in the subsurface will provide for treatment over prolonged period of time
- Order of oxidant persistence
  - Permanganate > Persulfate > Hydrogen Peroxide > Ozone

Methods of Oxidant Injection

- Sands
  - Direct Push
  - Conventional Injection Wells
  - Pressure Pulse Injection
- Clays
  - Large Diameter Augers
  - Electrokinetic's
- Bedrock
  - Surface Infiltration
  - Hydraulic Fracturing & Emplacement
  - Pneumatic Fracturing & Injection

Overburden Applications



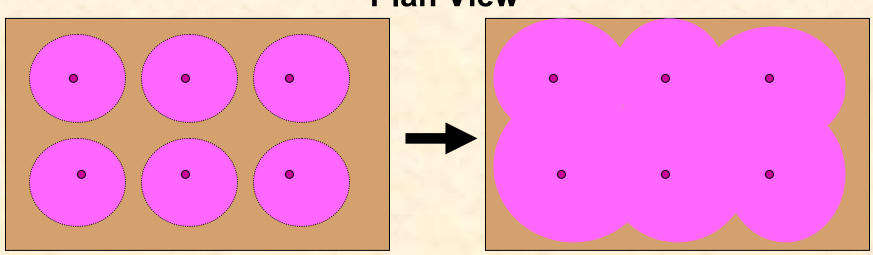
Direct Push

- Injection through drilling rods
- Temporary or fixed injection points
- Used in an array typically 10 to 20 feet on center
- Flexible delivery method, can customize injection intervals
- Limited by installation depth
- Moderate cost

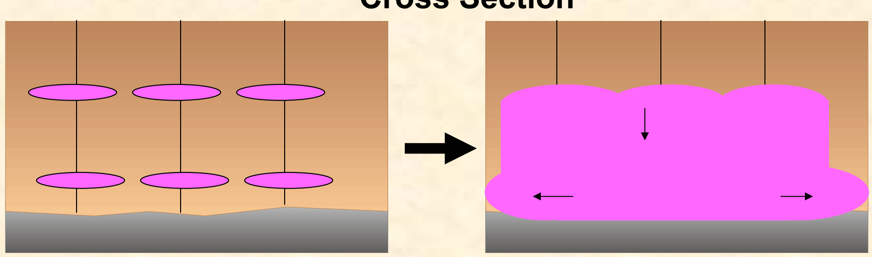
Source: University of Waterloo, Canada

Conceptual Approach - Coalescing Discs

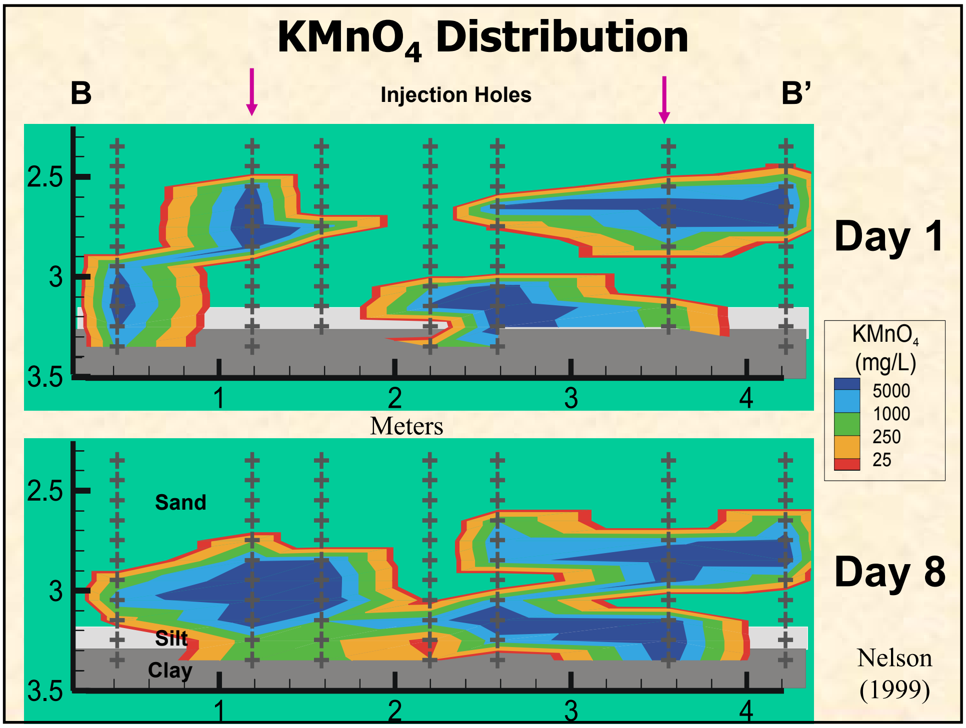
Plan View



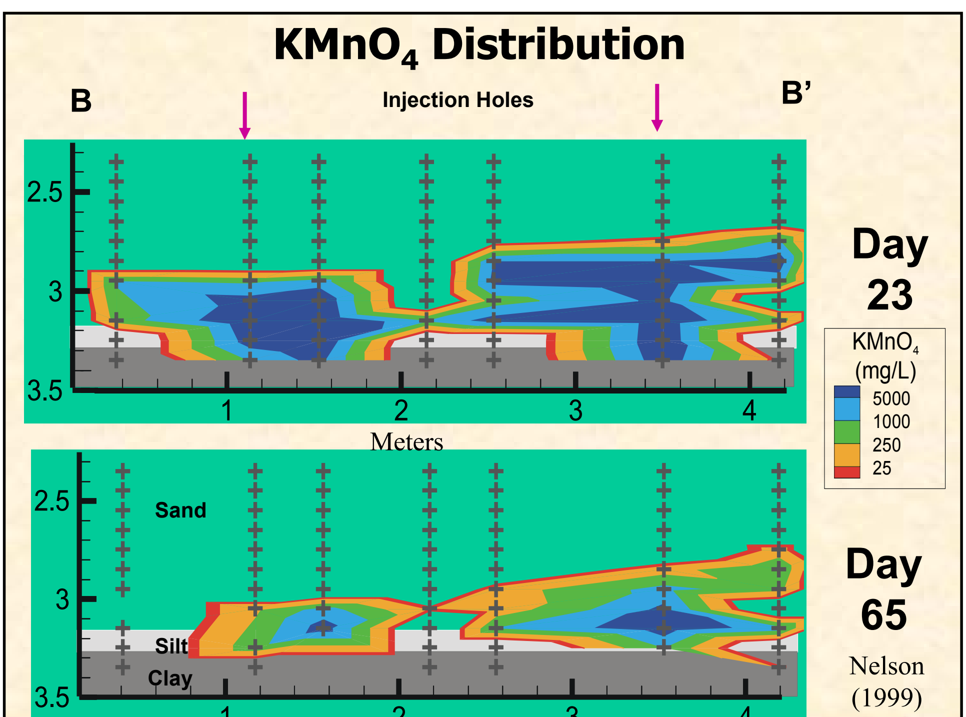
Cross Section



Nelson (1999)



KMnO4 Distribution
B
Injection Holes
B'
2.5
3
3.5
1
2
3
4
Meters
Day 1
KMnO4 (mg/L)
5000
1000
250
25
Sand
Silt
Clay
Day 8
Nelson (1999)



KMnO4 Distribution
B
Injection Holes
B'
2.5
3
3.5
1
2
3
4
Meters
Day 23
KMnO4 (mg/L)
5000
1000
250
25
Sand
Silt
Clay
Day 65
Nelson (1999)

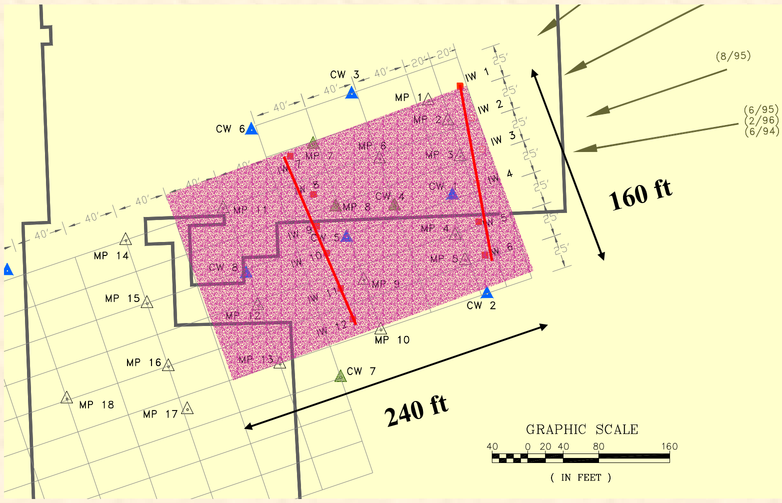
Conventional Injection Wells

- **Standard well construction**
- **Low pressure injection (0 to 30 psi)**
- **Used in an array or transects**
- **Relies on groundwater/density advection and dispersion for distribution**
- **Oxidant distribution limited by screen placement and soil heterogeneity**

DUOX Application (Persulfate/Permanganate)

- Active Manufacturing facility
- Water bearing strata: gravely-sand, semi-confined, 8-10 ft thick, 5 ft/day velocity
- Residual DNAPL in silt lenses at an aquitard interface
- Main contaminants: TCE, cis-DCE, VC
- Generally reducing groundwater conditions (ORP: 0 to –150 mV)

DUOX Injection Well Layout



DUOX Batching System

- **Fully Automated**
- **Minimized Oxidant Handling**
- **Persulfate ~ 8,200 kg (2 months)**
- **KMnO4 ~ 45,000 kg (6 months)**

DUOX Summary

- > 3,000 kg TCE DNAPL destroyed due to
  - Direct oxidation by persulfate/permanganate
  - Enhanced anaerobic bioremediation
- Monitored Natural Attenuation currently being evaluated for remaining dissolved TCE plume

XPERT DESIGN AND DIAGNOSTICS, LLC

Fenton's Reagent In-Situ Chemical Oxidation of TCE Source Area NTC Orlando, Florida

Steve Tsangaris – CH2M Hill Constructors, Inc.

Barbara Nwokike – SOUTHDIV NAVFAC

Dan Bryant – Geo-Cleanse International, Inc.

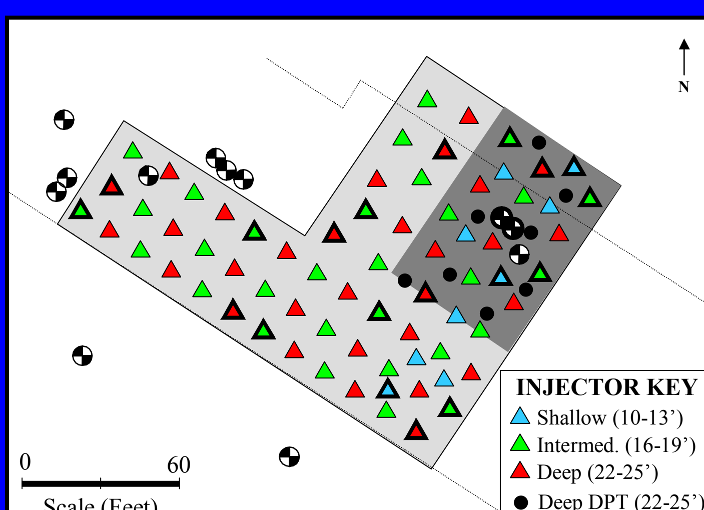
Naval Facilities Engineering Command Southern Division

CH2MHILL

Study Area 17

- NTC Orlando operationally closed under BRAC (1999).
- Former Motor Pool area.
- Buildings at SA 17 used for general storage, USTs.
- Initial site investigations began in 1995.
- Past remedial actions included 185-yd^3 excavation of PAH-contaminated soil.

Phase I Injector Installation & Sampling Locations

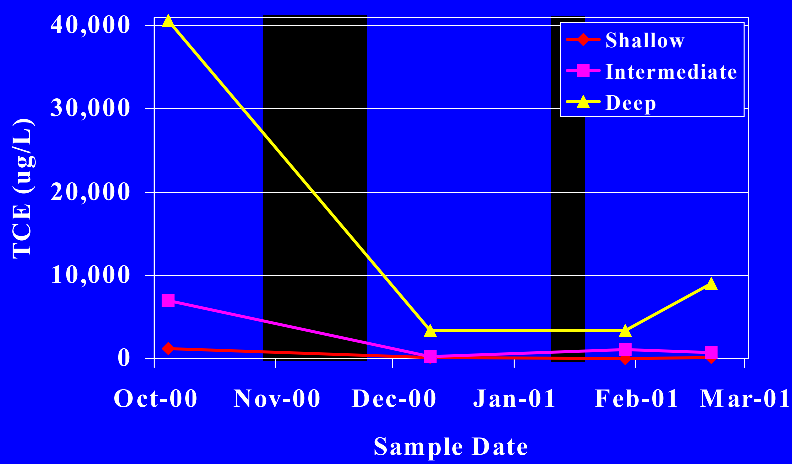


Study Area 17

Field Injection

- 2 Mobilizations
  - Nov. 7 – Nov. 30, 2000
  - Jan. 15 – Jan. 18, 2001
- 21 Days of Treatment
- 77 Injectors in 3 levels
- 6,307 Gallons of Hydrogen Peroxide

Injection Results
TCE Zonal Averages



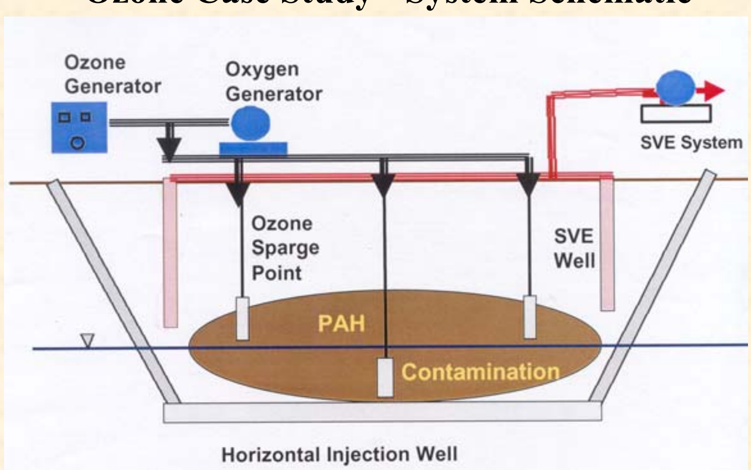
SA 17 Treatment Summary

- Phase I - Completed 21 days of injection.
  - 6,307 gallons of hydrogen peroxide
  - 77 injectors
- Achieved remedial objective in shallow zone (no significant rebound after 2 months).
- Significant reductions in intermediate and deep zone with associated chloride production.
- Additional delineation in progress (deeper than 31 feet below grade) for Phase II treatment.

Ozone Case Study

- Former manufactured gas plant (MGP)
- Site under an elevated roadway interchange
- Tar, oils, and lamp back
  - PAHs ~ 2,500 mg/kg
  - TPH ~ 28,000 mg/kg
- Treatment target 1 mg/kg BaP for soil

Ozone Case Study - System Schematic



1. Oxidation of PAH and TPH
2. Enhanced bioremediation through oxygen enrichment
3. Vapor collection

Ozone Case Study
Vertical Sparging Points

33 Points Installed to 25 ft

IT Corporation

Ozone Case Study
Horizontal Well Installation

- **Total length: 360 ft**
- **Screen length: 135 ft**
- **Install 6 feet below water table**
- **Install through center of plume**

IT Corporation

Ozone Case Study

Oxygen Generation Trailer

- **Molecular sieve – ambient air**
- **95% O_2 at 100 psi**

Ozone Generation Trailer

- **50 lb/day capacity**
- **5% O_3 at 15 psi & 7 scfm**

IT Corporation

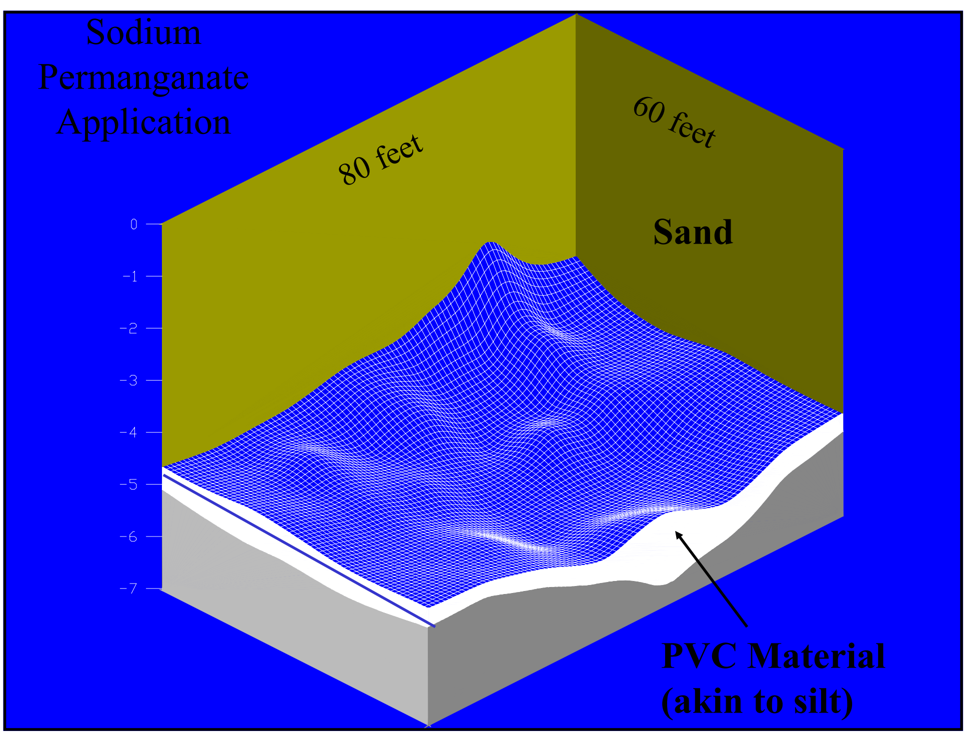
Ozone Case Study Results

- Free Product
  - Free product appeared after 4 months of operation
  - Decreasing overall percentage of heavy hydrocarbons (C13-C34)
  - Increase of lighter chains (C5-C10)
- Groundwater
  - Contaminant concentrations at or below detection limits by third quarter
- Soil
  - Target contaminants below detection limit by fourth quarter
- Site Closure for Industrial Risk Achieved

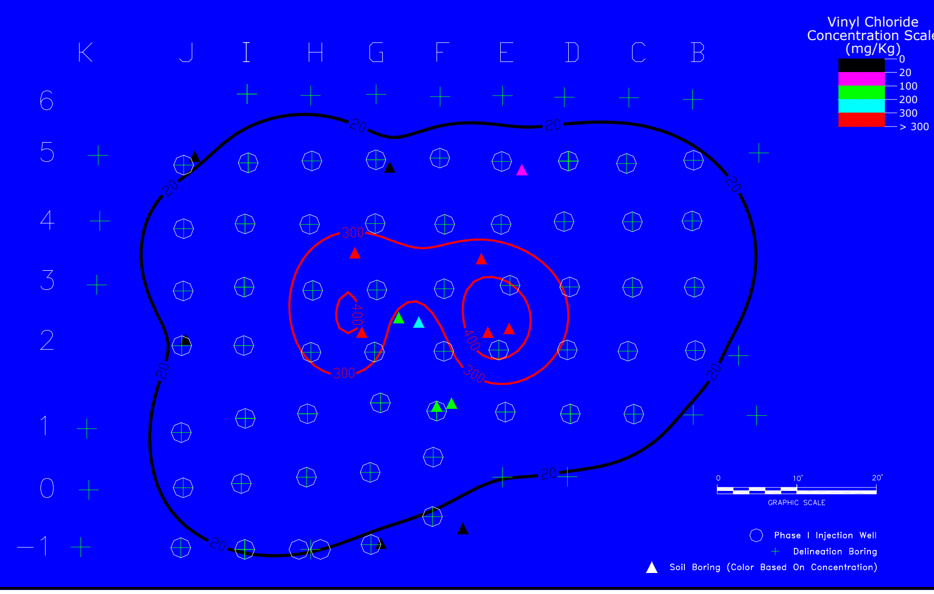
IT Corporation

Applications in Silts/Clays

- Oxidant Stability Key
- Pin-Cushion Approach
- Large Diameter Auger
- Electrokinetic's



Injection Well Layout



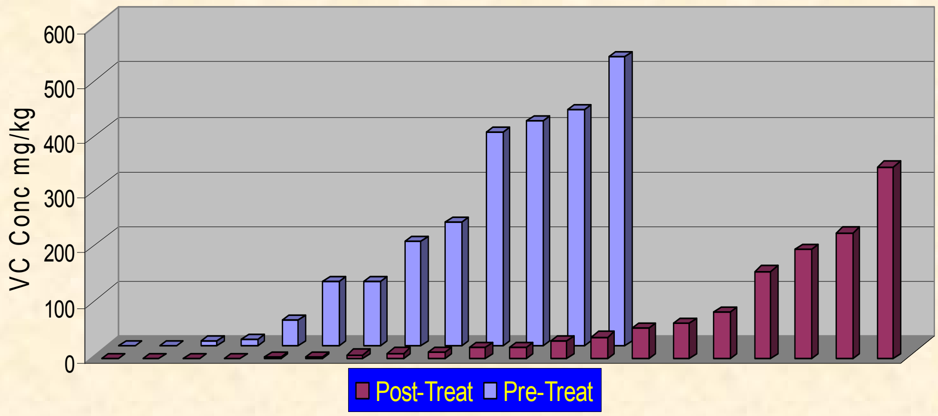
Portable Oxidant Delivery (POD) System

- Two injection events (20 days total)
- 55 injection points at 8 ft spacing
- Simultaneous multi-point injection
- 4,000 lbs $NaMnO_4$
- Fully self-contained

Source: XDD, LLC

Xpert Design and Diagnostics, LLC

Soil VC Concentrations
Pre-Treat vs. Post-Treat



XPERT DESIGN AND DIAGNOSTICS, LLC

Sodium Permanganate – Silts/Clays: Results

- Distribution of oxidant non-uniform due to low permeability and heterogeneity
- VC concentrations reduced to below or near cleanup goal (20 mg/kg) in 70% of post-treatment soil samples
- VC mass destruction ~ 62%
- Progressive decline in soil VOC concentration observed over 3 month period
- No further action required for soils
- MNA for dissolved plume

XPERT DESIGN AND DIAGNOSTICS, LLC

Large Diameter Augers

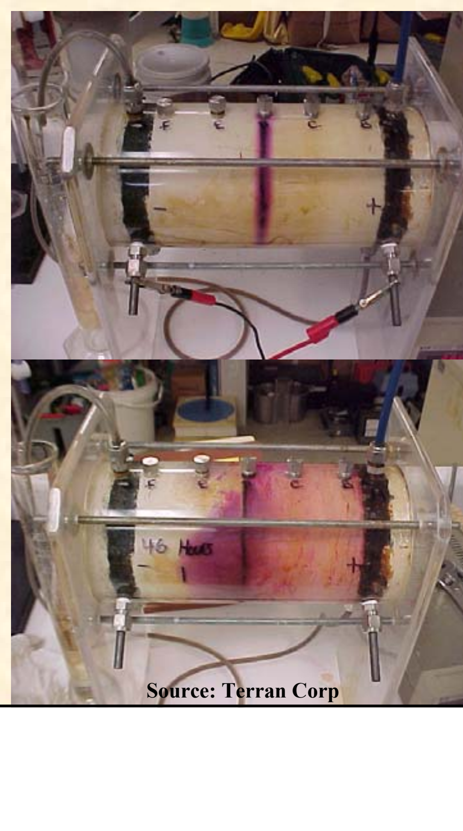
- 3 to 10 foot diameter augers equipped with injection nozzles
- Equipment developed for installing grout/cement pilings
- Uniform soil/oxidant mixing
- Limited by installation depth, subsurface utilities and structures
- High cost

Source: Office of Science and Technology (OST) Deep Soil Mixing ID:52 http://tms.em.doe.gov/

XPERT DESIGN AND DIAGNOSTICS, LLC

Electrokinetic Migration in Clay

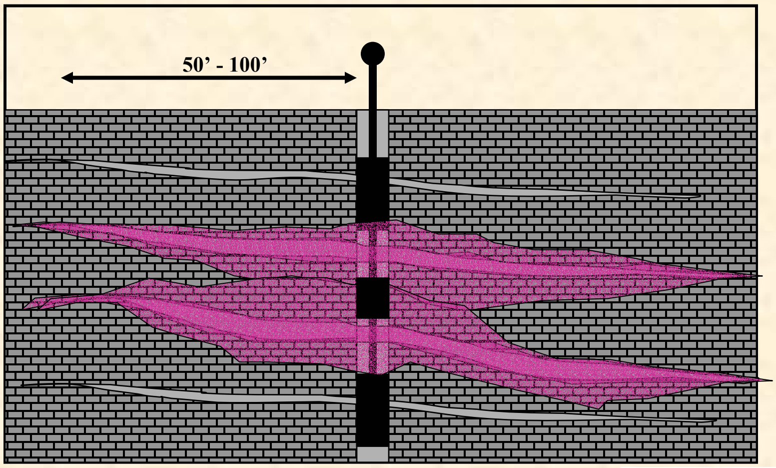
- Kaolin Clay ~ 37% moisture content
- $KMnO_4$
- 20 volts, 6 mA
- Current increases with $KMnO_4$ coverage
- Applicable to persulfate



Source: Terran Corp

XPERT DESIGN AND DIAGNOSTICS, LLC

Bedrock Applications



Surface Infiltration

- Superfund Site in Maine
- Vertically Fractured Rock
- PCE DNAPL to 110 ft
- Overburden (2 to 4 ft) Removed
- Vadose Zone ~ 30 ft
- Pilot Test ~ 300 kg $KMnO_4$
- 150 ft ROI
- GW [PCE] 30 mg/L to < 1 mg/L
- Rebound observed

Hydraulic Fracturing

- High pressure liquid injection to propagate fracture network
- Emplacement of sand or solid oxidant into fractures
- Injection of oxidants through sand filled fractures
- Applicable to low permeable formations/ bedrock

Source: FRx, 2002

XPERT DESIGN AND DIAGNOSTICS, LLC

Pneumatic Fracturing/Injection

- High pressure nitrogen gas injection to propagate fracture network
- Liquid oxidant injection through fracture network
- Applicable to low permeable formations/bedrock

Source: XDD, LLC

XPERT DESIGN AND DIAGNOSTICS, LLC

Pneumatic Fracturing/Injection

- **PCE/TCE DNAPL in clay 5 - 10 ft bgs**
- **Injection pressure = 100 psi**
- **Gas flow rate = 2000 scfm**
- **Oxidant flow rate = 50 gpm**
- **95% reduction**
- **Non-uniform distribution**

Liquid sodium permanganate is more hazardous to handle than solid potassium permanganate, but easier to batch.

XPERT DESIGN AND DIAGNOSTICS, LLC

Thank You!

XPERT DESIGN AND DIAGNOSTICS, LLC